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CARBON FOOTPRINTING

Comparison of product carbon footprint standards with a case study on poinsettia (*Euphorbia pulcherrima*)

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Abstract
Purpose A method to quantify the climate impact of products called product carbon footprint (PCF) has been gaining popularity in recent years. However, variations of this method have resulted in several competing standards to guide the carbon calculation process. The aim of the current paper was to compare PCF results when calculated according to the different standards.
Methods The three leading PCF standards are Publicly Available Specification (PAS) 2050:2011, ISO.DIN 2 14067 and Product Life Cycle Accounting and Reporting Standard (PARS) 2011. These standards were compared conceptually, and a case study was performed in which the PCF of a poinsettia plant produced in Germany was calculated according to all three standards.
Results and discussion The PCF results were 0.45–0.50, 0.53–0.58 and 0.53–0.59 kg carbon dioxide equivalent according to PAS 2050:2011, ISO.DIN 2 14067 and PARS 2011, respectively. According to all standards, the life cycle stage contributing the most greenhouse gases (GHGs) was the production of the poinsettia plant, and the single process with the highest emissions was the electricity use in the production. It was found that if nonrenewable fuels were used for heating instead of wood chips, then heating would be the highest GHG contributor—accounting for over 80 % of emissions of the total PCF.
Conclusions A key finding was that both the production system used and the decisions taken by the person carrying out the PCF calculation result in greater differences in the PCF result than the use of different standards. Differences among the three standards could be harmonised by more specific cut-off rules and exclusion criteria with the publication of ISO.DIN 2 14067, as well as the development and use of product category rules.

Keywords Horticulture · ISO.DIN 2 14067 · PAS 2050 · Poinsettia · Product carbon footprint (PCF) · Product Life Cycle Accounting and Reporting Standard

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1 Introduction

The increasing concentration of greenhouse gases (GHGs) in the atmosphere is a daily topic for governments, international organisations and companies. The rise of carbon dioxide (CO_2) concentration in the atmosphere, from 280 ppm in the pre-industrial period to over 385 ppm today (Hansen et al. 2008), results mainly from deforestation and burning fossil fuels (Sachs 2009). GHGs not only cause the change in the global temperature but also contribute to a number of environmental hazards. Rising ocean levels, habitat destruction, increased disease transmission, acidification of the oceans and changes in agricultural productivity and water availability are all linked to GHGs (Sachs 2009).

Driving global GHG emissions is the use of fossil fuels for the production and consumption of goods and services (together referred to as products) (Sinden 2009). Inherent in these sources of impact, though, is the potential to alleviate environmental problems (Paavola 2001). Producers can reduce the environmental impact of products by increasing their energy efficiency, by streamlining logistics, by using less toxic materials or by redesigning products to require fewer materials. Environmental impact can also be reduced

through consumer purchase decisions: by deciding to limit overall consumption by not buying a product or by choosing a product with the lowest environmental impact.

Interestingly, an organisation called the Carbon Trust (2012) claims that, regardless of a product's actual carbon footprint (PCF), consumers prefer products which are labelled accordingly. If a PCF label is displayed on a package, the Carbon Trust found that 49 % of consumers are more likely to buy the product. Resonating even more strongly, 65 % of consumers declared that a label indicating supplier commitment to reducing GHG emissions would make them more likely to buy the product.

ISO.DIN 2 14067 (International Organization for Standardization 2012) defines PCF as the sum of GHG emissions and removals in a product system, expressed as carbon dioxide equivalent (CO_2e) and based on a life cycle assessment. As public awareness on climate change increases, simplified and supposedly easy-to-understand indicators to express environmental impact, such as PCF, are increasingly called for (Feifel et al. 2010; Schmidt 2009). Therefore, PCF has become a hot topic for both companies and governments (Dangelico and Pujari 2010; Peters 2010; Röös et al. 2011). On the one hand, PCF claims to simplify the communication of results to a wide audience (Feifel et al. 2010; Peters 2010) because the result of the PCF calculation is a numeric value, though PCF does not give a full picture of a product's environmental impact and customers do not grasp what the PCF numeric value means (Brécard et al. 2009).

The development of PCF, so far, has not been driven by research but, rather, by promotion from non-governmental organisations, companies and various private initiatives (Weidema et al. 2008). Hence, PCF has developed into an important tool in green marketing (Stichnothe 2009) and branding (Carbon Trust 2008), rather than a regulating tool for climate change mitigation. This has resulted in a variety of standards guiding the PCF calculations, including the following:

- Product Life Cycle Accounting and Reporting Standard (PARS) (Greenhouse Gas Protocol 2011a)
- Publicly Available Specification (PAS) 2050:2011—specification for the assessment of the life cycle greenhouse gas emissions of goods and services (British Standards Institution 2011)
- ISO.DIN 2 14067 Carbon footprint of products—requirements and guidelines for quantification and communication (International Organization for Standardization 2012)

Each of these standards is considered a market leader in the international PCF calculation practice (Galeano 2009), and all of them are based on the life cycle assessment standards ISO 14040 and ISO 14044, which are both issued by the International Organization for Standardization (2006a, b). ISO.DIN 2 14067 and PARS also guide the communication of the PCF result to different target groups. Additionally, several countries have developed national PCF guidelines, such as General Principles for the Assessment and Labeling of Carbon Footprint of Products TS Q 0010:2009 in Japan (JEMAI 2009), and other PCF initiatives, e.g. in Italy, Korea, Sweden, Taiwan and Thailand (PCF World Forum 2012).

With several competing methodologies, the need for harmonising the methodology has emerged. Although the general principles of calculating PCF are the same in all standards, methodological differences may lead to different PCF results when different standards are used. Two studies have examined this potential. In the first study, the Greenhouse Gas Protocol (2011b) compared the methodologies of PARS and PAS 2050:2011. In the second, Dias and Arroja (2012) compared the methodologies of PAS 2050:2008, ISO 14040:2006, ISO 14044:2006 and the Confederation of European Paper Industries framework for PCF calculation (of paper and board products with a case study on office paper). Both studies concluded that the use of different methodologies gives different PCF results.

Due to the fact that PCF studies have not been published for all types of products, it is not clear if the methodological differences impact the results in the same way for all products. Several studies have been published on the PCF of horticultural products for food (e.g. Page et al. 2012; Schäfer and Blanke 2012; Reinhardt et al. 2009), but little information is available on the PCF of non-food horticultural products (e.g. comparison of PCF of roses from Kenya and the Netherlands) (Williams 2007). Valuable information on the impact of methodological differences for PCF calculation of horticultural products is still missing.

To provide further insight into PCF calculation for horticultural products, the current study compares the PCF of a poinsettia plant (*Euphorbia pulcherrima*) according to three PCF standards: PAS 2050:2011, PARS 2011 and ISO.DIN 2 14067 (later referred to as PAS 2050, PARS and ISO 14067, respectively). During the goal and scope definition as well as during the data collection, in March and April 2011, no valid Product Category Rules (PCR) were available for decorative horticultural products. In 2012, the British Standards Institution (2012) published PAS 2050–1 Assessment of life cycle GHG emissions from horticultural products. Future studies about horticultural products should consider these supplementary requirements for the cradle to gate stages of GHG assessments undertaken in accordance with PAS 2050.

The aim of this study is to investigate the following:

1. If the use of different standards impacts the PCF result,
2. Which aspects cause differences in the case study,

3 How much each life stage and emission source contributes to the PCF and
4 Which additional aspects may cause differences when the standards are conceptually compared.

2 Methods

In the following subsections, the methodological procedure of PCF calculation is described for all single steps to highlight the differences of the compared standards PAS2050, PARS and ISO 14067. A summary of the differences among the standards based on a theoretical comparison is provided in Table 1.

2.1 Goal definition

All standards agree that a PCF study may have different goals, ranging from internal product life cycle analysis to the external PCF communication. ISO 14067 specifies that the study goal must state the reasons for carrying out the study, the intended application and the audience. All standards can be used for reaching different study goals. The goal of the case study presented in this paper was to provide an illustrative PCF result for analysing GHG emissions throughout the life cycle of an example product, the poinsettia plant.

2.2 Functional unit

PAS 2050 states that the mass of CO_2e must be reported per functional unit for the product. PARS requires the functional unit to include the magnitude, duration and quality. ISO 14067 says that the functional unit must be clearly defined and measurable and, exceptionally, a PCF may be reported on a self-selected product unit basis. In the current study, the function of the product is decorating. The functional unit is a Christmas time room decoration in a form of a potted plant which stays fresh for at least 5 weeks starting from the first Advent. The time of the year is essential since similar products cultivated during the summer months would require less energy input. The PCF is reported on a product unit basis, which is one poinsettia plant ready for sale in a pot with a 12-cm diameter at the upper edge (later referred to as a 12-cm pot). This is in accordance with ISO 14067 and PAS 2050.

2.3 Scope definition and system boundary

2.3.1 Scope

All analysed standards allow the PCF to be calculated for cradle-to-grave and cradle-to-gate systems. ISO 14067 adds that the scope should be consistent with the study goal. The current study comprises GHG emissions from cradle to grave. However, since the case study serves as an example to show the differences among the standards, all life cycle stages where no primary data were available, such as the use stage, were modelled as scenario-based.

2.3.2 Included life cycle stages and processes

PARS states that all attributable processes must be included. PAS 2050 requires inclusion of all processes that make a material contribution, i.e. create emissions more than 1 % of the expected result, and ISO 14067 specifies that when PCR are used, their requirements on the processes to be included shall be applied. Furthermore, ISO 14067 requires inclusion of all life stages when study results will be communicated to the public. The ISO standard also specifies that life cycle stages may only be omitted if information on these specific stages is not available and reasonable scenarios cannot be modelled, or if emissions from these stages are insignificant.

Material acquisition, production, use and end-of-life stages were included in this study (Fig. 1). The distribution and the point of sale were excluded based on the assumption that no emissions occurred during these stages. The included stages are defined below:

1 *The material acquisition* stage includes two scenarios. The first scenario involves plant cutting production by a specialised producer. In this scenario, cuttings are taken from the mother plant and propagated until mature. The cuttings are then transported to the place of the poinsettia production, in the current case to the greenhouse of the University of Applied Sciences Weihenstephan-Triesdorf (HSWT). A second scenario involves pot and soil production, with subsequent transport to HSWT.
2 *The production* stage takes place in the HSWT, where the cuttings are planted into plastic pots and cultivated for 18 weeks until the poinsettia plants are ready for sale.
3 *The use* stage starts when the customer buys the poinsettia plant. It is based on a scenario where the customer drives to the shop with a personal car, waters the plant at home and disposes of the poinsettia after 8 weeks.
4 *The disposal* stage includes transport of different types of waste to the incineration and biogas plant and to the composting location, the following incineration and biogas production and composting processes. Carton and plastic waste is burned as part of a regular household waste in an incineration plant with energy recovery. It is assumed that the energy produced from biowaste in the combined electricity and heat plant substitutes for heat and electricity production elsewhere, based on nonrenewable energy carriers. All disposal scenarios are based on the local waste management systems (Westermeier and Hofmann 2011), where 50–70 % of biowaste is used for biogas production and the remaining amount is composted (Stippl 2013, personal communication).

Table 1 Overview of the differences among the PCF standards PAS2050:2011, PARS 2011 and ISO.DIN 2 14067

	PAS 2050:2011	PARS 2011	ISO.DIN 2 14067
Aspects which *cause* differences in the PCF calculation result			
Included life cycle stages and processes	All processes that make a material contribution, i.e. more than 1 % of the expected result	All attributable processes	Requirements of Product Category Rules (PCR) shall apply. All life stages if the results are planned to be made public. Exclusion of life cycle stages if no information is available and scenarios cannot be modelled or emissions are insignificant
Cut-off criteria	Exclusion of processes contributing less than 1 % if inventory is completed at least to 95 %, production of capital goods, transport of consumers and employees	Exclusion of emission sources which are insignificant based on mass, energy or volume and are irrelevant GHG emission sources	Exclusion of life cycle stages, processes, inputs or outputs if they do not significantly change the overall results
Global warming potential (GWP) factor	100-year GWP except where otherwise specified	100-year GWP, other assessment periods allowed	100-year GWP
Allocation	In order of preference: (1) performing allocation by process subdivision or system expansion, (2) PCR guidance and (3) economic allocation	In order of preference: (1) avoiding allocation by process subdivision, redefining the functional unit or system expansion; (2) performing allocation by physical relationships; and (3) economic or other allocation method	In order of preference: (1) avoiding allocation by process subdivision or system expansion, (2) performing allocation by physical relationships and (3) performing allocation by economic relationships
Allocation at the end-of-life stage (reuse and recycling)	Closed loop approximation and recycled content method (closed-loop and open-loop allocation in the ISO standard, respectively)	Closed-loop approximation and recycled content method	Closed-loop and open-loop allocation
PCR	Encourages the use of PCR if they fulfil the standard's requirements	Allows the use of PCR unless it conflicts with the standard	PCR or sector-specific guidance should be used
Aircraft emissions	No radiative forcing multiplier shall be applied	If a radiative forcing multiplier is used, then it should be disclosed in the inventory report	Aircraft emissions shall be included and documented separately. Reference to IPCC regarding the radiative forcing impact
Carbon stored in the product	Stored carbon for over 100 years shall be recorded	Carbon not released to the atmosphere during the waste treatment is considered stored and shall be reported	If carbon storage in products is calculated, it shall be documented separately but not included in the PCF result
Changes in the soil carbon content	Changes in the soil carbon content, except for changes resulting from land use change (LUC), shall be excluded unless provided for in PCR	Soil carbon change as a result of land use practices may be included	Unless included in the LUC, the soil carbon change should be calculated and included
Aspects which *do not cause* differences in the PCF calculation result			
Data collection	Primary data of processes, which contribute at least 10 % to the upstream emissions and are under the ownership or control of the organisation. Guidance for some special cases is provided	Primary data of processes under the ownership or control of the organisation	Measured, calculated or estimated qualitative and quantitative data are collected for all unit processes in the system boundaries. Significant unit processes shall be documented
Land use change (LUC)	LUC is included following, in order of preference: (1) PCR, (2) annex provided by the standard and (3) IPCC methodology	Direct LUC is calculated based on IPCC methodology, using the worst case scenario, is allowed. Indirect LUC may be calculated but must be separately reported	When significant, the direct LUC shall be assessed in accordance with internationally recognised methods. Indirect LUC should be considered, once an internationally agreed procedure exists

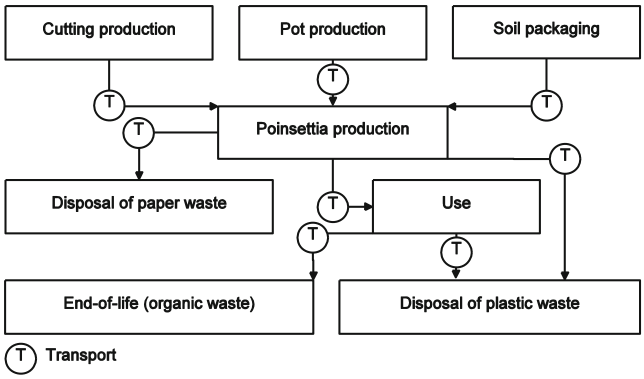

Fig. 1 System boundary including processes of the PCF of poinsettia

Table 2 Number of materials considered within the system boundary of the PCF of poinsettia

Material	Number of materials considered in the system boundary		
	PAS 2050:2011	ISO.DIN 2 14067	PARS 2011
Transport and fuel	1	4	14
Waste	2	4	4
Agricultural chemicals	0	1	2

2.3.3 *Cut-off criteria*

Cut-off criteria define which processes can be excluded from the inventory. According to PAS 2050, processes that contribute less than 1 % to the expected final result may be left out of the inventory, if the inventory is at least 95 % complete after excluding those emissions. It is worth noting that, after the PAS 2050 update in 2011, there is no longer a requirement to upscale the initial result to reflect 100 % emissions. PARS requires inclusion of all emission sources that, based on mass, energy or volume, are considered significant and that are relevant GHG emission sources. According to ISO 14067, deletion of life cycle stages, processes, inputs or outputs is allowed if such deletions do not significantly change the overall results. In the current case study, conforming to PAS 2050, all processes contributing over 1 % to the final result were included. For calculation according to PARS, all processes were considered relevant to illustrate the full inventory. In reference to ISO 14067, consistent cut-off criteria that allow the omission of certain processes of minor importance were defined. In the current study, it was decided to exclude all processes contributing less than 0.001 g of CO_2e. The application of different cut-off criteria resulted in excluding some transport and fuel emissions, as well as waste and agricultural chemicals for ISO 14067 and PAS 2050 (as presented in Table 2).

Additionally, according to PAS 2050, emissions and removals arising from the production of capital goods, transport of consumers to and from the point of retail purchase and transport of employees to and from their normal place of work shall be excluded. PARS adds that weighting factors for delayed emissions, offsets and avoided emissions (except for avoiding allocation) should also be excluded. According to ISO 14067, no delayed emissions shall be included in the PCF if all GHG emissions and removals from the product use or end-of-life stage occur within 10 years after the product has been brought to use. All emissions related to poinsettia life cycle occur in less than 10 years. In the current case study, emissions from capital goods, employee transport, heating and electricity used in other areas except for the greenhouse, materials (divided by thousands of pots or plants, such as packages of agricultural chemicals), organic waste resulting at the production stage, one fungicide and six insecticides were excluded when ISO 14067 was used. The contribution of emissions from those sources to the final PCF was considered negligible. These exclusions are in accordance with each analysed standard. In addition, when the PCF is calculated according to PAS 2050, customer transport is also excluded.

2.4 Global warming potential

PAS 2050 and ISO 14067 state that the latest available Intergovernmental Panel on Climate Change (IPCC) 100-year global warming potential (GWP) coefficients should be used. PARS also allows the use of other assessment periods. In the current case study, the IPCC (2007) assessment for a time frame of 100 years is used.

2.5 Biogenic carbon

All standards require including biogenic emissions and removals. Biomass-based carbon that is captured during the poinsettia cultivation is partly converted into biogas and partly emitted during composting at the end-of-life stage.

2.6 Data collection

ISO 14067 requires qualitative and quantitative data for the life cycle inventory to be collected for all unit processes that are included in the system boundaries. PARS and PAS 2050 add that primary data should be collected for all processes under the ownership or control of the organisation carrying out the PCF calculation and that data quality is assessed during the data collection process. PAS 2050 adds a specific

requirement regarding the amount of emissions that the organisation carrying out the PCF calculation should contribute to the final PCF:

> Where the organisation carrying out the PCF calculation does not contribute 10 % or more to the upstream GHG emissions prior to its provision to another organisation or to the end user, the collection of primary activity data shall apply to the emissions arising from processes by the organisation and any upstream supplier that cumulatively contribute 10 % or more to the upstream GHG emissions.

PAS 2050 provides additional guidance for collecting data in the following special cases:

1 Changes in the product's life cycle;
2 Variability in emissions;
3 Data sampling;
4 Non-CO_2 emissions (nitrous oxide and methane) data for livestock and soils;
5 Emissions data for fuel, electricity and heat including emissions associated with renewable electricity generation; and
6 Emissions from biomass and biofuels.

In the poinsettia case study, primary data were collected for the processes under the HSWT control. Secondary data (e.g. estimations provided by the professionals of the HSWT poinsettia production facility during interviews) (Haas 2011; Sauer 2011, personal communication), data provided by the ecoinvent version 2.2 database (Ecoinvent Centre 2010) and GaBi professional database (PE International 2011) were used for creating scenarios. Data sources for activity data and emission source are presented in Table 3. Data were gathered about each emission source and their quality was assessed. The data collection took place outside of the poinsettia growing season, in April 2011, which is why some measurements were not possible and estimations by the professionals were used instead. Weather conditions greatly influence the necessary energy input in the greenhouses. The average energy input over several years should be used for poinsettia PCF inventory, if the study goal is to calculate the PCF result for product comparisons. The current study measured the poinsettia PCF for the production period from August to December 2010.

Table 3 Data sources for the activity data and emission factors used to estimate the PCF of poinsettia

Emission sources	Data source	
	Activity data	Emission factor
Cutting production		
Fertiliser use	Scenario	GaBi professional database (GaBi PD) (PE International 2011)
Electricity use	Scenario	GaBi PD
Packaging material	HSWT, scenario	GaBi PD
Water	Scenario	GaBi PD
Pot production		
Injection moulding	HSWT, scenario	ecoinvent (ecoinvent Centre 2010)
Packaged soil		
Packaging material	HSWT, scenario	ecoinvent (ecoinvent Centre 2010)
Peat	HSWT	GaBi PD
Production		
Heating	HSWT	GaBi PD
Electricity use	HSWT	GaBi PD
Fertiliser production and use	HSWT	GaBi PD
Water	HSWT	GaBi PD
Use		
Transport by passenger car	Scenario	ecoinvent (ecoinvent Centre 2010)
Water	HSWT, scenario	GaBi PD
Disposal		
Disposal of paper waste	Freising town, scenario	GaBi PD
Disposal of plastic waste	Freising town, scenario	GaBi PD
Energy production from biowaste	Scenario	GaBi PD
Substituted electricity production	Scenario	ecoinvent (ecoinvent Centre 2010)
Composting	Kägi and Wettstein (2010)	Kägi and Wettstein (2010)
Transport		
Distances	Freising town, scenario	GaBi PD
Truck and fuel use	–	GaBi PD
GHG emissions from fuel burning and production	–	GaBi PD

Material acquisition Cutting production includes peat pellets as substrate, fertiliser and electricity use, and carton tray for packaging. It is based on a scenario for which the data were provided by the professional HSWT poinsettia growers. Packaging material was measured at HSWT. Emission factors were provided by GaBi professional database (PE International 2011). Pot production consists of an injection moulding process. Material quantity used for the pot production was measured at HSWT, and the scenario for production is based on the process data provided in the ecoinvent version 2.2 database (Ecoinvent Centre 2010). According to the 2008 and 2012 product catalogues of substrate producers Floragard and Plantaflor, respectively, the poinsettia substrate for cultivation consists of

a mixture of over 80 % peat and approximately 15 % perlite. Additionally, it includes clay, calcium carbonate, surfactant and nitrogen–phosphorus–potassium fertiliser. Therefore, in the current study, for the purpose of simplification, it is assumed that the substrate consists only of peat and is packaged in a low-density polyethylene bag.

The amount of soil used per one plastic pot, as well as the quantity of material used for the packaging, was measured at HSWT. The transport distance for cuttings is the average distance from 11 poinsettia cutting producers in Germany to HSWT. The plastic pot is transported from the central wholesale point from the middle of Germany. The peat is transported from the extraction location in northern Germany. All of the transport processes are based on scenarios. The fuel use and GHG emissions are provided by the GaBi professional database (PE International 2011).

Production The poinsettia production consists of electricity, fertiliser and water use, and heating. It is modelled according to the actual poinsettia (*E. pulcherrima*) cultivation system "Cool Morning–Warm Evening" in the HSWT and compared to the conventional production system, which runs in parallel in the HSWT greenhouses. The data on production were either measured in the HSWT (heating) or calculated based on the data provided by the professional HSWT poinsettia producers (electricity, water and fertiliser applied during the cultivation).

Use The use stage starts when the customer buys the poinsettia plant. The use stage is based on a scenario in which the customer drives to the shop by a personal car and the poinsettia plant is a proportional part of customer's shopping bag. The water quantity for watering the plant during the use stage is modelled according to the recommendations by the professional HSWT poinsettia producers.

Disposal The data for the disposal stage, including transport distances, are provided by the local authority. The scenario is based on the Freising local waste management practices (Westermeier and Hofmann 2011). According to Wurzer Umwelt GmbH, the actual waste management company, 50–70 % of organic waste brought to them from Freising is used for biogas production and the rest is directly composted. Therefore, the following two end-of-life scenarios were investigated: 50 % biogas/50 % composting and 70 % biogas/30 % composting. The emissions resulting from road maintenance are included as provided in the GaBi professional database (PE International 2011).

2.7 Calculation

The PCF calculation was done with the LCA software program GaBi 5 (PE International 2011). All three standards state that, to obtain PCF results, the activity data, such as electricity use, fuel use, distance travelled, amount of material consumed, etc., must be multiplied by the respective emission factor. In the current PCF calculation, the emission factors were provided by the aforementioned ecoinvent and GaBi databases. The result should be multiplied by the characterisation factors according to the most recent data provided by IPCC (2007). Also, ISO 14067 and PAS 2050 provide a list of IPCC characterisation factors in their annexes.

2.8 Allocation

When one process produces several valuable outputs, the three standards require process subdivision or system expansion as a first choice to distribute the GHG emissions between these outputs. However, there are differences in the wording. PAS 2050 calls the above-described process *allocation*, while PARS and ISO standard call it *avoiding allocation*. If process subdivision or system expansion is not possible, then system outputs should be allocated following PARS and ISO 14067, in order of preference, based on physical, economic or other relationships. PAS 2050 requires in the second place to follow PCR, which may suggest allocation based on physical or mass properties. Lastly, allocation based on economic value is carried out. For allocation taking place at the end-of-life stage (reuse and recycling), PAS 2050 states that the following calculation should be applied:

$$\text{GHG emissions} = (a + f)/b + c + d + e$$

where a is the life cycle emissions, excluding use stage; b is the anticipated number of reuse cycles; c is emissions arising from a cycle of preparing the product for reuse; d is emissions of the use stage; e is emissions from transport returning the product for reuse; and f is emissions arising from disposal.

PARS and ISO standards present two options for recycling scenarios. The first option is closed-loop allocation (in PARS closed-loop approximation method), for product systems where no changes occur in the inherent properties of the recycled material. The second option is open-loop allocation (in PARS recycled content method), for product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

In the current study, at the production stage, allocation was performed for the heating with wood chips. According to Haas (2013, personal communication), wood chips are the result of regular clearing works in the nearby forest, gardens, road sides and tree nurseries. Therefore, the emissions resulting from wood chipping, transport and other pre-

combustion processes were allocated equally between the local waste management and greenhouse heating processes regardless of the standard used. Since generic process data were used, allocation based on concrete physical or economical data was not possible.

At the end-of-life stage, allocation was first performed by mass between the organic waste being used for biogas production and composting. For biogas production, allocation was avoided by system expansion. Biogas produced from the organic waste was assumed to replace an equal amount of heat (natural gas) and electricity (national grid average) produced by an alternative nonrenewable fuel-based system. For the GHG savings by these substitutions, GHG credits were granted. For composting, data about GHG emissions based on economic allocation between waste management service and sold compost were used (Kägi and Wettstein 2010).

3 Results

The PCF result in the case study was in the range of 0.45–0.50 kg CO_2e according to PAS 2050, 0.53–0.58 kg CO_2e according to ISO 14067 and 0.53–0.59 kg CO_2e according to PARS per one poinsettia plant in a 12-cm pot ready for sale. The range shows the differences between the reference production system Cool Morning–Warm Evening and the conventional production system as well as between the end-of-life scenarios 70 % of organic waste to biogas production and 30 % to composting, and 50 % biogas production/50 % composting. The impacts of these other production system and end-of-life scenarios are presented in Table 4.

Minor differences between ISO 14067 and PARS are created by excluding all GHG emissions below 0.001 g CO_2e in the case of PARS. That exclusion criterion resulted in leaving out emissions resulting from fertiliser use for the poinsettia cutting production and all transportation processes, except for transport of plant waste and truck use with road maintenance for transporting the pot and soil. In the case of PAS 2050, excluding customer transport by personal car to the point of sale resulted in reduction in the final PCF result of poinsettia by 14 % in the Cool Morning–Warm Evening production system with the end-of-life scenario 70 % biogas/30 % composting. The rest results from excluding all emissions contributing less than 1 % to the final PCF result. Therefore, all agricultural chemicals and most of transport- and waste disposal-related emissions were excluded. Emissions higher than 1 % result only from eight processes:

1 Electricity use for poinsettia production,
2 Heating for poinsettia production,
3 Customer transport by personal car,
4 Electricity use for poinsettia cutting production,
5 Production of plastic pot,
6 Incineration of plastic pot in the incineration plant,
7 Truck use for biowaste transport and
8 Composting organic waste.

The calculation complies with the 95 % inventory completion requirement. If customer transport is excluded from the calculation, according to PARS, then the result according to PAS 2050 would sum up to 98 % of the result according to PARS.

Total emissions and emissions by life stage for the Cool Morning–Warm Evening production system with the end-of-life scenario 70 % biogas/30 % composting are presented in Fig. 2. According to all standards, poinsettia production was the most emission-intensive life stage, constituting approximately 78 % of total emissions for PARS and ISO 14067 and approximately 91 % for PAS 2050. For PARS and ISO 14067, the use stage also contributed over 12 % of total GHG emissions. Organic waste end-of-life management, including composting and substituted electricity production, reduces the overall PCF result approximately 13 % in the case of PARS and ISO standards and over 15 % in the case of PAS 2050. Disposal of materials other than biowaste contributes approximately 5 %, and material acquisition stage contributes about 4 %.

The main source of GHG emissions according to all standards is electricity use for poinsettia production, namely, 64 % for PARS and ISO 14067 and 74 % for PAS 2050. It is followed by heating, with 8 % for PARS and ISO 14067 and 9 % for PAS 2050. In HSWT, wood chips are used for producing thermal energy. According to all three standards, CO_2 emissions from wood biogenic carbon are considered neutral. The heating GHG emissions result from the transport and pre-combustion processes. If nonrenewable fuels would be used for heating, the emissions would be remarkably higher, namely, more than 50 times higher in the case of heating oil (as presented in Table 5). The total PCF would

Table 4 Impact of different production systems and end-of-life scenarios on the total PCF

Production system	PARS	ISO 14067	PAS 2050
"Cool Morning–Warm Evening"			
30 % composted, 70 % biogas	0.0 %[a]	−0.1 %	−15.9 %
50 % composted, 50 % biogas	5.6 %	5.5 %	−10.4 %
Conventional			
30 % composted, 70 % biogas	4.6 %	4.5 %	−11.3 %
50 % composted, 50 % biogas	10.2 %	10.1 %	−5.7 %

[a] Baseline 0 %, the reference system with the production system "Cool Morning–Warm Evening" and the end-of-life scenario 30 % composting, 70 % biogas production, modelled according to PARS

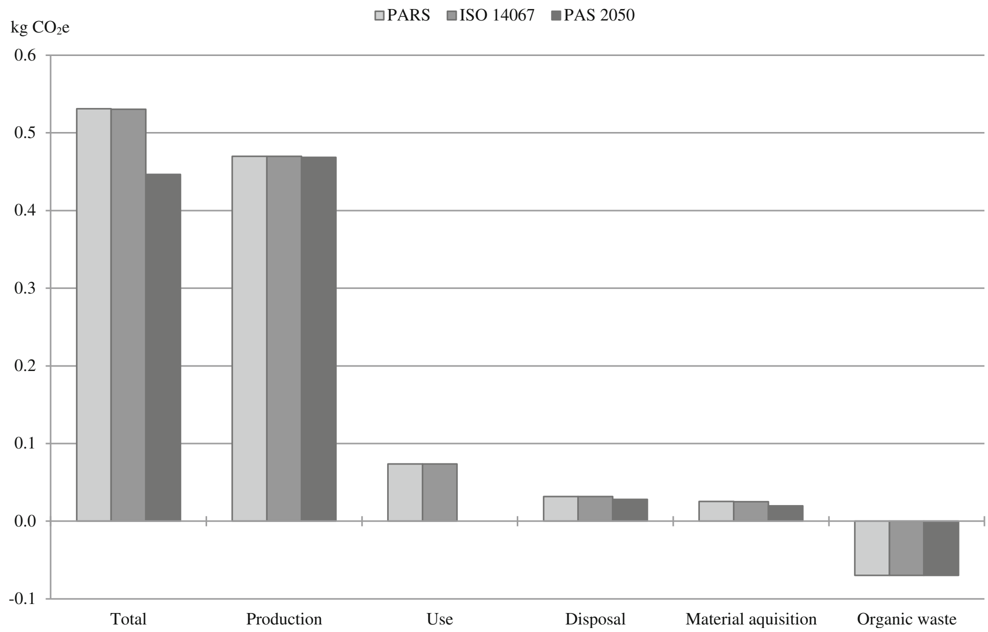

Fig. 2 Life cycle stages GHG emissions of PCF of poinsettia based on the reference system with the "Cool Morning–Warm Evening" production system and the end-of-life scenario 70 % biogas production/30 % composting

be more than five times higher, and heating would constitute over 80 % of the total PCF. For this comparison, the organic waste management, including composting and biogas production, was excluded from the inventory. The result is comparable regardless of the standard used.

4 Discussion

Use of the three different standards resulted in three numerically different PCF results. The main reasons for the different results obtained were the application of different exclusion criteria and cut-off rules.

When only a few processes contribute to the majority of emissions (e.g. if wood chips are replaced with heating oil in the poinsettia production process), then, according to PAS 2050, only heating, electricity use for the poinsettia production and electricity use for the cutting production contribute over 1 % of total emissions. This makes the data collection process easier than with other standards. As PAS 2050 required, customer transport was excluded from the inventory and resulted in a 14 % reduction in the PCF result. On the one hand, customer transport may have a significant contribution to the total PCF and should not be left out, especially for products which cannot be transported without a motorised vehicle. On the other hand, the organisation carrying out the PCF calculation usually has little or no means to influence customer shopping habits and therefore should not be held responsible. Clearer guidance on the use stage methodology should be provided either in the PCF standards or PCR.

Dias and Arroja (2012) conclude that different cut-off criteria and allocation caused differences in the PCF results. The Greenhouse Gas Protocol (2011b) adds that some change in results may also be caused by using different PCR and allocation and minor changes may be caused by different definition of system boundaries (such as inclusion of soil carbon, stored carbon in products, time period for assessment and aircraft emissions). Theoretically, some differences may also be caused by using different functional units, obtaining more data from the primary sources than requested, and different calculation programs.

Both case studies, the one performed by Dias and Arroja (2012) and the other presented in this paper, indicate that, in practice, only a few aspects cause differences in the final PCF results. The theoretical comparison of standards as presented by the Greenhouse Gas Protocol (2011b) shows that several more aspects may influence the final result. These discussed issues are not solved in the currently available ISO 14067 draft. More widespread use of sector-specific guidance may solve some of these methodological differences (Greenhouse Gas Protocol 2011b).

Table 5 CO_2e emissions from different energy sources for heating

Energy source	Heating, kg CO_2e (%)	Total PCF, kg CO_2e (%)	Heating fraction in total PCF (%)
Wood chips	0.05 (100)	0.60 (100)	8
Natural gas	2.12 (4,240)	2.68 (446)	79
Heating oil	2.85 (5,700)	3.40 (566)	84

This case study showed that the PCF results in the same production system with the same end-of-life scenario for organic waste according to analysed standards differ up to 16 %. When PCF calculation of one product is carried out using PAS 2050, then the results may be lower compared to a calculation according to PARS because of different cut-off rules. That also applies, in both cases, if customer transport is excluded. The difference between PARS and PAS 2050 was approximately 2 %. However, this can be considered insignificant since the range of emissions at the organic waste end-of-life stage cause the PCF to differ more than 5 % (see Table 4), which is within the expected uncertainty range. Therefore, product comparisons based on their PCF should only be encouraged if all aspects that can potentially cause differences in the final results are dealt in the same way. Preferably, the same standard should be used.

The poinsettia case study also showed that PCF results are influenced more by different production systems than the use of different standards. A separate study on eight different types of tomato growing systems in different geographical locations indicated that the PCF of 1 kg of tomatoes ranged from 0.1 to 1.5 kg CO_2e and that 80 % of greenhouse tomato production emissions can result from heating (Theurl 2011). Our study showed that emissions from wood chip-based heating ranked second after the emissions from electricity use. Scenarios with nonrenewable fuels for heating showed that the respective emissions would increase more than 50 times if heating oil would be used. This would be over 80 % of the total PCF and increase the total PCF more than five times. Since heating is the most energy-demanding process in greenhouses in most European countries, it should be seen as a hotspot for climate impact of products.

5 Conclusions

The main conclusions that can be drawn from the study are as follows:

1. The PCF results according to PAS 2050, PARS and ISO 14067 differ. In the poinsettia case study, the results were 0.45–0.50, 0.53–0.59 and 0.53–0.58 kg CO_2e according to PAS 2050, ISO 14067 and PARS, respectively, per one poinsettia plant in a 12-cm pot.
2. The differences in the PCF results were caused by different cut-off and exclusion rules and requirements for the use stage but can be considered insignificant except for the customer transport. The rule for leaving out customer transport in the case of PAS 2050 caused a 14 % difference in the final result. Several issues at the user stage still need to be researched, such as acquiring primary data about customer transport and actual customer behaviour. Answers to these questions help to determine if the user stage could be omitted from the PCF calculation because of its marginal contribution to the final PCF. Unanimous principles for the use stage methodology should be provided either in the PCF standards or PCR.
3. According to all standards, the poinsettia production process resulted in the highest GHG emissions. For horticultural products grown in greenhouses in Germany, heating and lighting consume the most energy. Therefore, the choice of fuels determines the magnitude of GHG emissions. Replacing wood chips with heating oil increased the total PCF more than five times.
4. Aspects such as GWP factor, allocation, allocation at the end-of-life stage, PCR, aircraft emissions, carbon stored in the product and changes in the soil carbon content may also cause differences in the PCF result. However, it should be considered that the person carrying out the study may cause greater differences in the PCF results with his decisions on different aspects than the PCF standards. Therefore, for product comparisons, the same decisions for aspects that may cause differences should be taken.

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